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The $B \rightarrow \pi\pi, \pi K$ Puzzles: Implications for Hadron Physics, New Physics and Rare Decays

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Abstract

The B -meson system is an interesting probe for the exploration of strong interactions, the quark-flavour sector of the Standard Model, and the search for new physics. In this programme, non-leptonic B decays, which are particularly challenging from the point of view of QCD, play a key rôle. After discussing strategies to deal with the corresponding hadronic matrix elements of four-quark operators and popular avenues for new physics to manifest itself in B decays, we focus on puzzling patterns in the B -factory data for $B \rightarrow \pi\pi, \pi K$ decays; we explore their implications for hadron physics, new physics and rare K and B decays.

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THE $B \rightarrow \pi\pi, \pi K$ PUZZLES: IMPLICATIONS FOR HADRON PHYSICS, NEW PHYSICS AND RARE DECAYS

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The B -meson system is an interesting probe for the exploration of strong interactions, the quark-flavour sector of the Standard Model, and the search for new physics. In this programme, non-leptonic B decays, which are particularly challenging from the point of view of QCD, play a key rôle. After discussing strategies to deal with the corresponding hadronic matrix elements of four-quark operators and popular avenues for new physics to manifest itself in B decays, we focus on puzzling patterns in the B -factory data for $B \rightarrow \pi\pi, \pi K$ decays; we explore their implications for hadron physics, new physics and rare K and B decays.

Keywords: $B \rightarrow \pi\pi, \pi K$ puzzles; new physics; rare K and B decays.

1. B Physics in a Nutshell

In this decade, there are continuing huge experimental efforts to explore the quark-flavour sector of the Standard Model (SM): BaBar (SLAC) and Belle (KEK) have already collected $\mathcal{O}(10^8)$ $B\bar{B}$ pairs, first B -physics results are coming from run II of the Tevatron (FNAL), second generation B -decay studies will start at the LHC (CERN) in 2007, and there are various plans to measure rare kaon decays. In this programme, the B -meson system is a particularly interesting playground, with challenging aspects of strong interactions, avenues to obtain valuable insights into weak interactions, and probes to search for “new physics” (NP); for a detailed recent discussion, see Ref. 1. A key rôle is played by non-leptonic B decays, which may receive contributions from tree, QCD penguin and electroweak (EW) penguin topologies. In order to deal with these processes, low-energy effective Hamiltonians are used, which are calculated by means of the operator product expansion, yielding transition amplitudes of the following structure:²

$$\langle f | \mathcal{H}_{\text{eff}} | B \rangle = \frac{G_F}{\sqrt{2}} V_{\text{CKM}} \sum_k C_k(\mu) \langle f | Q_k(\mu) | B \rangle, \quad (1)$$

where G_F is Fermi’s constant, V_{CKM} a factor containing the corresponding elements of the Cabibbo–Kobayashi–Maskawa (CKM) matrix, and μ denotes a renormalization scale. The Q_k are local operators, which are generated through the interplay between electroweak interactions and QCD, and govern “effectively” the decay in

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question, whereas the Wilson coefficients $C_k(\mu)$ describe the scale-dependent “couplings” of the interaction vertices that are associated with the Q_k . In this formalism, the short-distance contributions are described by the perturbatively calculable Wilson coefficients $C_k(\mu)$, whereas the long-distance physics arises in the form of hadronic matrix elements $\langle f|Q_k(\mu)|B\rangle$. These non-perturbative quantities are the key problem in the theoretical analyses of non-leptonic B decays. Although there were interesting recent developments in this field through QCD factorization (QCDF),³ the perturbative hard-scattering (PQCD) approach,⁴ soft collinear effective theory (SCET),⁵ and QCD light-cone sum-rule methods,⁶ as discussed at this conference in the plenary talks by Beneke, Cheng, Du and Bauer, the B -factory data indicate that the theoretical challenge remains (see, for instance, Refs. 7–10).

Fortunately, it is possible to circumvent the calculation of the hadronic matrix elements for the exploration of CP violation:

- Amplitude relations can be used to eliminate the hadronic matrix elements. We distinguish between exact relations, using pure “tree” decays of the kind $B \rightarrow KD$ or $B_c \rightarrow D_s D$, and relations, which follow from the flavour symmetries of strong interactions, and involve $B_{(s)} \rightarrow \pi\pi, \pi K, KK$ modes.
- In the neutral B_q systems ($q \in \{d, s\}$), the interference between $B_q^0-\bar{B}_q^0$ mixing and decay processes may lead to “mixing-induced CP violation”. If a single CKM amplitude dominates the decay, the hadronic matrix elements cancel in the corresponding CP asymmetries; otherwise we have to use amplitude relations again.

These two avenues offer various strategies to “overconstrain” the unitarity triangle (UT) of the CKM matrix through studies of CP violation in the B system.¹ Moreover, “rare” decays, which originate from loop processes in the SM, provide valuable complementary information; important examples are $B \rightarrow K^*\gamma$, $B \rightarrow \rho\gamma$, $B_{s,d} \rightarrow \mu^+\mu^-$ and $K \rightarrow \pi\nu\bar{\nu}$ transitions. In the presence of NP effects in the quark-flavour sector, we expect to encounter discrepancies with the picture emerging from the CKM mechanism. Popular ways for NP to manifest itself are the following:

- $B_q^0-\bar{B}_q^0$ mixing: NP may enter through the exchange of new particles in box diagrams, which contribute in the SM, or through new contributions at the tree level, thereby modifying the mixing parameters as follows:

$$\Delta M_q = \Delta M_q^{\text{SM}} + \Delta M_q^{\text{NP}}, \quad \phi_q = \phi_q^{\text{SM}} + \phi_q^{\text{NP}}. \quad (2)$$

Whereas the NP contribution ΔM_q^{NP} to the mass difference would affect the determination of one UT side, the NP contribution ϕ_q^{NP} to the weak mixing phase would enter the mixing-induced CP asymmetries. Because of the remarkable agreement between the direct determination of the UT angle β through $B_d \rightarrow J/\psi K_S$ and the CKM fits,¹¹ the space for NP is getting smaller and smaller in the B_d system. On the other hand, the B_s system is still essentially unexplored, and will be a key target for LHCb.

- *Decay amplitudes:* NP has typically a small effect if SM tree processes play the dominant rôle, as in $B_d \rightarrow J/\psi K_S$. On the other hand, we encounter potentially large effects in the flavour-changing neutral-current (FCNC) sector. For instance, new particles may enter in penguin diagrams, or new FCNC processes may arise at the tree level. Interestingly, there are hints in the current B -factory data for such effects. In particular, Belle results for $B_d \rightarrow \phi K_S$ raise the question of whether $(\sin 2\beta)_{\phi K_S} = (\sin 2\beta)_{\psi K_S}$, and the branching ratios of certain $B \rightarrow \pi K$ decays show a puzzling pattern.

In the following, we will focus on the latter “ $B \rightarrow \pi K$ puzzle”, which was already indicated by the first CLEO data for the $B_d^0 \rightarrow \pi^0 K^0$ decay in 2000,¹² and received a lot of attention recently (see, for instance, Refs. 13–16).

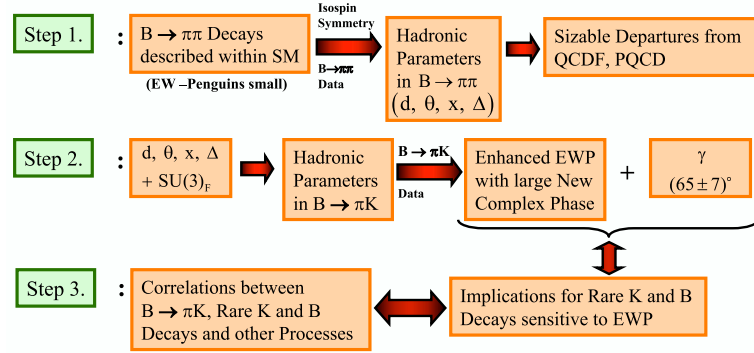


Fig. 1. The structure of a strategy to analyse the $B \rightarrow \pi K$ puzzle, as discussed in the text.

2. A Strategy for the Exploration of the $B \rightarrow \pi K$ Puzzle

In order to analyse the puzzling patterns in the $B \rightarrow \pi K$ data, we use the strategy in three subsequent steps developed in Ref. 7, as illustrated in Fig. 1; the numerical values refer to the recent update given in Ref. 17.

2.1. Step 1: $B \rightarrow \pi\pi$

The $B \rightarrow \pi\pi$ system offers three decay channels, $B^+ \rightarrow \pi^+\pi^0$, $B_d^0 \rightarrow \pi^+\pi^-$ and $B_d^0 \rightarrow \pi^0\pi^0$, as well as their CP conjugates. Consequently, we may introduce the following two independent ratios of the corresponding CP-averaged branching ratios:

$$R_{+-}^{\pi\pi} \equiv 2 \left[\frac{\text{BR}(B^\pm \rightarrow \pi^\pm \pi^0)}{\text{BR}(B_d \rightarrow \pi^+ \pi^-)} \right] \frac{\tau_{B_d^0}}{\tau_{B^+}}, \quad R_{00}^{\pi\pi} \equiv 2 \left[\frac{\text{BR}(B_d \rightarrow \pi^0 \pi^0)}{\text{BR}(B_d \rightarrow \pi^+ \pi^-)} \right]. \quad (3)$$

The branching ratios for $B_d \rightarrow \pi^+\pi^-$ and $B_d \rightarrow \pi^0\pi^0$ are found to be surprisingly small and large, respectively, whereas the one for $B^\pm \rightarrow \pi^\pm \pi^0$ is in accordance with theoretical estimates. This feature is the “ $B \rightarrow \pi\pi$ puzzle”. In addition to the

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CP-conserving observables in (3), we may also exploit the following CP-violating observables of the $B_d \rightarrow \pi^+ \pi^-$ decay:

$$\frac{\Gamma(B_d^0(t) \rightarrow \pi^+ \pi^-) - \Gamma(\bar{B}_d^0(t) \rightarrow \pi^+ \pi^-)}{\Gamma(B_d^0(t) \rightarrow \pi^+ \pi^-) + \Gamma(\bar{B}_d^0(t) \rightarrow \pi^+ \pi^-)} = \mathcal{A}_{\text{CP}}^{\text{dir}} \cos(\Delta M_d t) + \mathcal{A}_{\text{CP}}^{\text{mix}} \sin(\Delta M_d t). \quad (4)$$

The experimental picture of these CP asymmetries is not yet fully settled.¹⁸ However, their theoretical interpretation discussed below yields constraints for the UT, in excellent agreement with the CKM fits obtained within the SM.

Using the isospin flavour symmetry of strong interactions, the observables in (3) and (4) depend on two (complex) hadronic parameters, $d e^{i\theta}$ and $x e^{i\Delta}$, which describe – sloppily speaking – the ratio of penguin to colour-allowed tree amplitudes and the ratio of colour-suppressed to colour-allowed tree amplitudes, respectively. It is possible to extract these quantities *cleanly* and *unambiguously* from the data:

$$d = 0.51_{-0.20}^{+0.26}, \quad \theta = +(140_{-18}^{+14})^\circ, \quad x = 1.15_{-0.16}^{+0.18}, \quad \Delta = -(59_{-26}^{+19})^\circ; \quad (5)$$

a similar picture is also found by other authors.^{8–10} In particular the impressive strong phases give an unambiguous signal for large deviations from “factorization”. In recent QCDF¹⁹ and PQCD²⁰ analyses, the following numbers were obtained:

$$d|_{\text{QCDF}} = 0.29 \pm 0.09, \quad \theta|_{\text{QCDF}} = -(171.4 \pm 14.3)^\circ, \quad (6)$$

$$d|_{\text{PQCD}} = 0.23_{-0.05}^{+0.07}, \quad +139^\circ < \theta|_{\text{PQCD}} < +148^\circ, \quad (7)$$

which depart significantly from the experimental pattern in (5).

Having the hadronic parameters given in (5) at hand, the CP-violating asymmetries of the $B_d \rightarrow \pi^0 \pi^0$ channel can be predicted:

$$\mathcal{A}_{\text{CP}}^{\text{dir}}(B_d \rightarrow \pi^0 \pi^0)|_{\text{SM}} = -0.28_{-0.21}^{+0.37}, \quad \mathcal{A}_{\text{CP}}^{\text{mix}}(B_d \rightarrow \pi^0 \pi^0)|_{\text{SM}} = -0.63_{-0.41}^{+0.45}, \quad (8)$$

offering the exciting perspective of large CP violation in this decay. The first results for the direct CP asymmetry were recently reported by the BaBar and Belle collaborations,²¹ corresponding to the average of $\mathcal{A}_{\text{CP}}^{\text{dir}}(B_d \rightarrow \pi^0 \pi^0) = -(0.28 \pm 0.39)$,¹⁸ which is in encouraging agreement with (8). In the future, more accurate input data will allow us to make much more stringent predictions.

2.2. Step 2: $B \rightarrow \pi K$

In contrast to the $B \rightarrow \pi\pi$ modes, which originate from $b \rightarrow d$ processes, we have to deal with $b \rightarrow s$ transitions in the case of the $B \rightarrow \pi K$ system. Consequently, these decay classes differ in their CKM structure and exhibit a different dynamics. In particular, the $B \rightarrow \pi K$ decays are dominated by QCD penguins. Concerning the EW penguins, we distinguish between the following cases: in $B_d^0 \rightarrow \pi^- K^+$, $B^+ \rightarrow \pi^+ K^0$ transitions, the EW penguin amplitudes are colour-suppressed and are hence expected to be tiny. On the other hand, EW penguins contribute also in colour-allowed form to the $B^+ \rightarrow \pi^0 K^+$, $B_d^0 \rightarrow \pi^0 K^0$ system and have therefore a significant impact on these modes.

The starting point of our $B \rightarrow \pi K$ analysis is given by the hadronic parameters determined in Subsection 2.1 and the CKM fits of the UT, which are only insignificantly affected by EW penguins. We then use the following working hypotheses:

- (i) $SU(3)$ flavour symmetry of strong interactions;
- (ii) neglect of penguin annihilation and exchange topologies.

Internal consistency checks of these assumptions can be performed. They are nicely satisfied by the current data, and do not indicate any anomalous behaviour. We may then determine the hadronic $B \rightarrow \pi K$ parameters through their $B \rightarrow \pi\pi$ counterparts, allowing us to predict the $B \rightarrow \pi K$ observables in the SM.

In the case of the observables with a tiny impact of EW penguins, we obtain agreement between the SM predictions and the data. In particular, our prediction $\mathcal{A}_{\text{CP}}^{\text{dir}}(B_d \rightarrow \pi^\mp K^\pm) = +0.127_{-0.066}^{+0.102}$ agrees nicely with the measurements of this direct CP asymmetry, which was observed by BaBar and Belle in the summer of 2004,²² with the average value $\mathcal{A}_{\text{CP}}^{\text{dir}}(B_d \rightarrow \pi^\mp K^\pm) = +0.113 \pm 0.01$. Moreover, assumptions (i) and (ii) listed above imply

$$H \propto \underbrace{\left(\frac{f_K}{f_\pi}\right)^2 \left[\frac{\text{BR}(B_d \rightarrow \pi^+\pi^-)}{\text{BR}(B_d \rightarrow \pi^\mp K^\pm)}\right]}_{0.38 \pm 0.04} = - \underbrace{\left[\frac{\mathcal{A}_{\text{CP}}^{\text{dir}}(B_d \rightarrow \pi^\mp K^\pm)}{\mathcal{A}_{\text{CP}}^{\text{dir}}(B_d \rightarrow \pi^+\pi^-)}\right]}_{0.31 \pm 0.11}. \quad (9)$$

The experimental numbers indicated in this expression give us further confidence in our working hypothesis. Furthermore, H allows us to convert the $B_d \rightarrow \pi^+\pi^-$ CP asymmetries into a value of γ , in excellent agreement with the fits for the UT. On the other hand, a moderate numerical discrepancy arises for the ratio R of the CP-averaged $B_d \rightarrow \pi^\mp K^\pm$, $B^\pm \rightarrow \pi^\pm K$ branching ratios. This feature suggests a sizeable impact of a hadronic parameter, $\rho_c e^{i\theta_c}$, which enters the most general parametrization of the $B^+ \rightarrow \pi^+ K^0$ amplitude. It can be constrained through the direct CP asymmetry of the decay $B^\pm \rightarrow \pi^\pm K$ and the emerging $B^\pm \rightarrow K^\pm K$ signal, and actually shifts the predicted value of R towards the data.

Let us now turn to those observables that are significantly affected by EW penguins. The key quantities are the following ratios:²³

$$R_c \equiv 2 \left[\frac{\text{BR}(B^+ \rightarrow \pi^0 K^+) + \text{BR}(B^- \rightarrow \pi^0 K^-)}{\text{BR}(B^+ \rightarrow \pi^+ K^0) + \text{BR}(B^- \rightarrow \pi^- \bar{K}^0)} \right] \stackrel{\text{Exp}}{=} 1.00 \pm 0.08 \quad (10)$$

$$R_n \equiv \frac{1}{2} \left[\frac{\text{BR}(B_d^0 \rightarrow \pi^- K^+) + \text{BR}(\bar{B}_d^0 \rightarrow \pi^+ K^-)}{\text{BR}(B_d^0 \rightarrow \pi^0 K^0) + \text{BR}(\bar{B}_d^0 \rightarrow \pi^0 \bar{K}^0)} \right] \stackrel{\text{Exp}}{=} 0.79 \pm 0.08, \quad (11)$$

where the EW penguin contributions enter in colour-allowed form through the decays with π^0 mesons in the final states. Theoretically, the EW penguin effects are described by the following parameters:

$$q \stackrel{\text{SM}}{=} 0.69, \quad \phi \stackrel{\text{SM}}{=} 0^\circ, \quad (12)$$

where q , which can be calculated in the SM with the help of the $SU(3)$ flavour symmetry,²⁴ measures the “strength” of the EW penguins with respect to the tree

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contributions, and ϕ is a CP-violating weak phase with an origin lying beyond the SM. EW penguin topologies offer an interesting avenue for NP to manifest itself, as has already been known for several years.^{25,26}

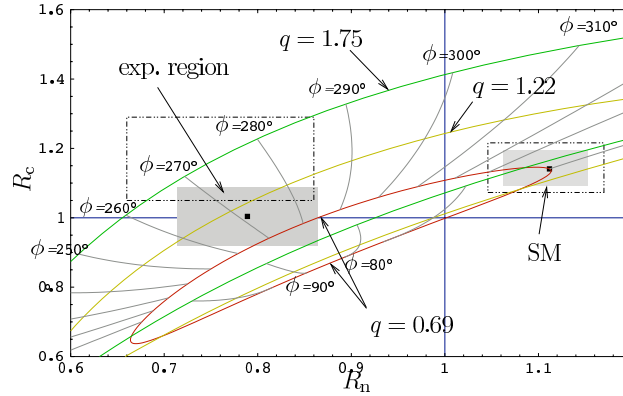


Fig. 2. The situation in the R_n – R_c plane, as discussed in the text.

In Fig. 2, we show the current situation in the R_n – R_c plane: the experimental ranges and those predicted in the SM are indicated in grey,¹⁷ and the dashed lines serve as a reminder of the corresponding ranges in Ref. 7; the central values for the SM prediction have hardly moved, while their uncertainties have been reduced a bit. Moreover, we show contours for values of $q = 0.69$, $q = 1.22$ and $q = 1.75$, with $\phi \in [0^\circ, 360^\circ]$. We observe that we arrive no longer at a nice agreement between our SM predictions and the experimental values. However, as becomes obvious from the contours in Fig. 2, this discrepancy can be resolved if we allow for NP in the EW penguin sector, i.e. if we keep q and ϕ as free parameters. Following these lines, the successful picture described above would not be disturbed, and we obtain full agreement between the theoretical values of $R_{n,c}$ and the data. The corresponding values of q and ϕ are given as follows:

$$q = 1.08^{+0.81}_{-0.73}, \quad \phi = -(88.8^{+13.7}_{-19.0})^\circ, \quad (13)$$

where in particular the large CP-violating phase would be a striking signal of NP. These parameters then allow us to predict also the CP-violating observables of the $B^\pm \rightarrow \pi^0 K^\pm$ and $B_d \rightarrow \pi^0 K_S$ decays,¹⁷ which should provide useful future tests of this scenario. Particularly promising in this respect are rare K and B decays.

2.3. Step 3: Rare K and B Decays

In order to explore the implications for rare K and B decays, we assume that NP enters the EW penguin sector through enhanced Z^0 penguins with a new CP-violating phase. This scenario was already considered in the literature, where model-independent analyses and studies within SUSY were presented.^{27,28} In our strategy,

we determine the short-distance function C characterizing the Z^0 penguins through the $B \rightarrow \pi K$ data. Performing a renormalization-group analysis,²⁹ we obtain

$$C(\bar{q}) = 2.35 \bar{q} e^{i\phi} - 0.82 \quad \text{with} \quad \bar{q} = q \left[\frac{|V_{ub}/V_{cb}|}{0.086} \right]. \quad (14)$$

If we then evaluate the relevant box-diagram contributions within the SM and use (14), we can calculate the short-distance functions:

$$X = 2.35 \bar{q} e^{i\phi} - 0.09 \quad \text{and} \quad Y = 2.35 \bar{q} e^{i\phi} - 0.64, \quad (15)$$

which govern the rare K, B decays with $\nu\bar{\nu}$ and $\ell^+\ell^-$ in the final states, respectively. In the SM, we have $C = 0.79$, $X = 1.53$ and $Y = 0.98$, with *vanishing* CP-violating phases. If we impose constraints from the data for rare decays, in particular those on $|Y|$ following from $B \rightarrow X_s \mu^+ \mu^-$, the following picture arises:

$$\bar{q} = 0.92_{-0.05}^{+0.07}, \quad \phi = -(85_{-14}^{+11})^\circ. \quad (16)$$

The corresponding predictions of R_c and R_n agree nicely with the data reported at the ICHEP '04 conference.³⁰ We may encounter significant deviations from the SM expectations for certain rare decays, with a pattern characteristic of our NP scenario. The most spectacular effects are the following ones:^{7,17,31,32}

- $K \rightarrow \pi\nu\bar{\nu}$: enhancement of $\text{BR}(K_L \rightarrow \pi^0\nu\bar{\nu})$ by up to one order of magnitude, and strong violation of the relation $(\sin 2\beta)_{\pi\nu\bar{\nu}} = (\sin 2\beta)_{\psi K_S}$.
- $K_L \rightarrow \pi^0 e^+ e^-$ and $K_L \rightarrow \pi^0 \mu^+ \mu^-$: now governed by direct CP violation, with branching ratios enhanced by $\mathcal{O}(3)$.
- $B_d \rightarrow K^* \mu^+ \mu^-$: a forward-backward CP asymmetry can be very large.
- $B \rightarrow X_{s,d} \nu\bar{\nu}$ and $B_{s,d} \rightarrow \mu^+ \mu^-$: branching ratios may be enhanced by factors as large as $\mathcal{O}(2)$ and $\mathcal{O}(5)$, respectively.

3. Conclusions

The $B \rightarrow \pi\pi$ data allow the clean extraction of hadronic parameters, which indicate large non-factorizable effects – thereby resolving the “ $B \rightarrow \pi\pi$ puzzle” – and favour large CP violation in $B_d \rightarrow \pi^0\pi^0$. The resulting SM analysis of the $B \rightarrow \pi K$ system agrees with the current data, with the *exception* of the observables receiving sizeable EW penguin contributions, which is another manifestation of the “ $B \rightarrow \pi K$ puzzle”. It can be resolved through NP in the EW penguin sector involving a large CP-violating phase. If NP enters through Z^0 penguins, we expect significant NP effects in rare K and B decays, with a pattern that is characteristic of this scenario. It will be interesting to confront these results with future, more accurate data.

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